

Water Mitigation of Explosion Effects

Part 1: The dynamic pressure from partially confined spaces

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Abstract

This work is a contribution to an ongoing co-operative research project between FOA in Sweden and TNO-PML in the Netherlands, aimed at investigating the physics of water mitigation and to formulate instructions and standards of how to use water barriers. FOA has focused on the scale-modeling laws and to investigate if the mitigation is affected when the charges are cased.

The technique of damping blast from high explosives with "water barriers" of different types has recently been studied by some research institutes and consultants. Examples on practical applications are to reduce the most severe hazard area around an ammunition storage, on equipment for manufacturing or the destruction of ammunition etc. However, the results reported in this field indicate that the mitigation effect from water is not yet fully understood. Although it has been demonstrated to work well in many tests in small scale, unexpected results have occurred when tested in full scale.

This paper contains a somewhat closer look on the blast mitigation effect from water for geometries similar to a duct attached to a confined space, e.g. an access tunnel in to an ammunition storage. Of special interest is then the dynamic pressure inside the access tunnel, caused by the shock and quasi-static pressure from an explosion in the storage chamber, as well as the jet formed outside the tunnel entrance. An effort is made to explain some results from scale model experiments in terms of elementary thermodynamics and shock wave theory. This is illustrated by a set of numerical simulations with the hydrocode AUTODYN using its two phase material model for water. The calculated results are compared with the experiments, and it is concluded that the numerical model to some extent describes the phenomena involved. Applied on real ammunition storage magazines these data, in short, indicate a substantial pressure reduction in the storage chamber, but possible problems with debris throw outside the access tunnel due to the high dynamic pressure in the flow.

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1. Background

The technique of water mitigation of explosion effects has recently been studied by several consultants and researchers (/1/, /2/, /3/, /4/, /5/, /6/, /15/, /16/, /17/). Examples on practical applications are to reduce the most severe hazard area around ammunition storage magazines, around equipment for manufacturing or the destruction of ammunition, or even around suspected terrorist bombs etc. An alternative is aqueous foam, the same type as is commonly used by fire-squads. Foam has been investigated quite well both experimentally and theoretically and is found to have a considerable damping effect on shock-waves both in the free air, in confined spaces as well as in tubes and tunnels. But as foam has no long-time stability, pure liquid water in suitable packages is instead considered for ammunition storages and other situations with lasting hazard areas. The problem of potential leakage of water is nowadays eliminated, due to plastic containers of different types, which are intended to break up only when exposed to a detonation (e.g. in /7/, where tests of one such product is reported).

The mitigation effect from water has been demonstrated to work well in many situations, but some unexpected results have also been reported. One example is a full scale test simulating a detonating ammunition storage in a rock tunnel, performed by the KLOTZ-Club in Alvdalen, Sweden in 1996 /3/. The results when water barrels were placed close to the charge were compared with a former test without water, but with the same charge and tunnel geometry. It was then found that the pressure, especially outside the tunnel, rather increased slightly than was reduced, as intended.

In this paper, the dynamic pressure from the water vapor flow from a partially confined space is modeled for a case when the water mitigation technique is used for an explosion in a chamber with an attached duct (the “shotgun” geometry). It also intends to give a somewhat broader view on the physics of the water mitigation technique, as well as on some other experiments reported.

2. Review of applicable physics

2.1 Shock-wave pressure. The air shock-wave is a complex, dynamic phenomenon which comprises both a wave and a flow simultaneously; its pressure can be measured and described in different ways. Figure 1 illustrates the fundamental difference between the *static pressure* and the *dynamic pressure* of a flow, inside and outside a tunnel. The static pressure, denoted p' , is the pressure of the compressed gas inside the wave, caused by the gaseous combustion products from the HE, superposed on the surrounding air pressure. One way to measure p' is with a transducer mounted with the diaphragm flush with the propagation direction (thereby it is also called “side-on” pressure). The dynamic pressure, denoted q is actually the kinetic energy of the moving gas, which is related to the drag force that a fix object experience when exposed to (i.e. surrounded by) the shock wave flow. The dynamic pressure is described by:

$$(1) \quad q = \frac{1}{2} v^2 \times \rho \quad \text{where } v \text{ denotes the velocity and } \rho \text{ the density of the gas flow.}$$

Clearly, this differs from the internal, static pressure of the gas as it depends only on the density and the velocity vector of the moving gas (although a relation between the dynamic and the static pressure do exist for shock-waves in defined situations).

A device to measure the dynamic pressure in a shock flow can be obtained if the above described “side-on” gage is supplemented with a transducer with its diaphragm mounted perpendicular to the flow direction, preferably on a thin nozzle with aerodynamic shape. This gage then senses the stagnation pressure p_{stag} , but according to /11/ p.45, a good estimation of the dynamic pressure is the difference between the stagnation pressure and the static pressure; it can therefore be calculated from the relation $q = (p_{\text{stag}} - p')$; this is relevant only in one direction, e.g. for one-dimensional flows.

In experiments with shock waves often only p' is measured; then one assumes that the properties of the gases in the shock flow are known. If the gases, however, have some unknown characteristics, it is important to measure also q to correctly describe the flow. This can be illustrated by a shock-wave in a tunnel that enters free air, figures 1 and 2. Inside the tunnel, the shape of the two different types of pressure traces coincide fairly well close to the wave front; at the rear part of the wave they differ a bit more and outside the tunnel they are entirely different.

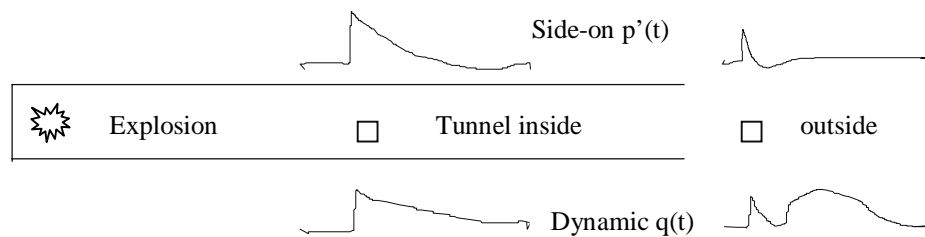


Figure 1. Air shock wave pressure traces from gages inside and outside a tunnel

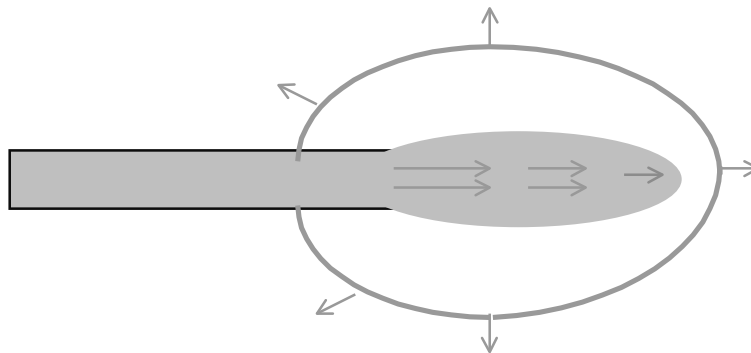


Figure 2. Shock-wave and flow outside a tunnel.

Two effects combine outside such a tunnel exit, as indicated in figure 2. When the shock wave reaches the open air, it immediately starts to expand in all directions as an almost spherical “shell” (as waves have no inertia) while the moving gas, due to its inertia forms a jet outside the tunnel which follows right behind the shock wave in the centerline direction. This explains the pressure histories in figure 1 where the p' -gage outside the tunnel only senses the pressure when the thin shell-formed shock wave passes, while the q gage first senses a sudden movement in the air when the shock wave passes, and then the long-duration force when it is reached by the jet; this is shown by authentic pressure recordings in the Appendix, also in /13/, /14/ and /17/. In /14/, experiments are reported with a shock tube with gages located in front of the tube exit which, together with shadow-graphs, show a jet that is quite narrow (a few tube diameters) up to some distance and then dissolves into eddies and disappears at larger distances, as shown in figure 3.

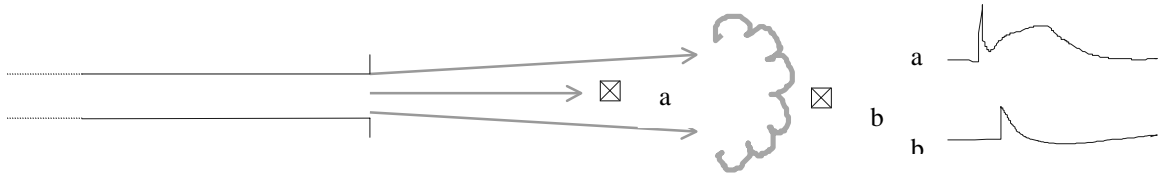


Figure 3. Stagnation pressure measurement on a jet, dissolved into eddies at large distances.

These experiments (with one-phase flow; helium was used as driver gas) indicate that the range of the jet is determined by the geometry of the duct, the exit pressure (i.e. the flow speed) and the duration of the flow. It was concluded, that several properties of the gases influence such a jet. Although the relations that describe all the situations above are complicated they can, to a large extent, be analyzed with well-defined ideal-gas models. Also, the behavior of the two-phase flow that occurs when a real gas like water vapor is added, is possible to analyze to some extent with simplified assumptions (as described in section 2.4).

2.2 Short about thermodynamics. When a mass amount (n moles) of an ideal gas undergoes an adiabatic compression or expansion, the pressure p , volume V and temperature T are related by the following equations (from [8]):

$$(2) \quad pV = nRT \quad (\text{General Gas Law})$$

$$(3) \quad pV^{(C_p/C_v)} = \text{constant} \quad (\text{Poisson's Law})$$

where C_p and C_v are the heat capacities at constant pressure and volume, respectively, and the gas constant $R = 8.314 \text{ J/mol K}$. From the relation $C_p = C_v + R \Rightarrow C_p/C_v > 1$ together with equation (2) and (3) above, it can be seen that the temperature always increases when a gas is compressed and decreases when expanded. The ideal gas model is a quite good approximation for most cases with a mix of air and detonation products like CO , CO_2 , NO_x etc. at moderate pressure levels (i.e. a few MPa). A real gas, like water vapor, differs somewhat from the equations above, e.g. when a real gas is expanded its temperature decreases more, which in some cases turns it into liquid or solid phase, while an ideal gas by definition always remains in gaseous phase.

To describe an agent at different phases, tables on its density, temperature, volume, internal energy etc. at different pressure values are used. Some relations can also be presented graphically, as for water in figure 4. Among other things, this shows that there is a certain range in pressure and temperature where water exists as a liquid. For temperatures beyond the critical point (647 K) it can't be in the liquid phase, no matter the pressure increase. On the other hand: if the pressure is very low, all the water will remain in the gaseous phase even when the temperature is decreased (and then turns directly into ice crystals at a very low temperature). In figure 4b, derived from figure 4a, the pressure-volume relation for the liquid-vapor region is plotted more in detail; the temperature is here implicit. A similar curve is piecewise implemented in the two-phase material model of the hydrocode "AUTODYN" [9].

It can be noted, that water vapor at high pressure and temperature has a higher density than air if the air is compressed from NTP (Normal Temperature and Pressure i.e. 273 K, 100 kPa) to a similar pressure. The opposite (i.e. lower density than air) is valid for HE gas, due to its high temperature.

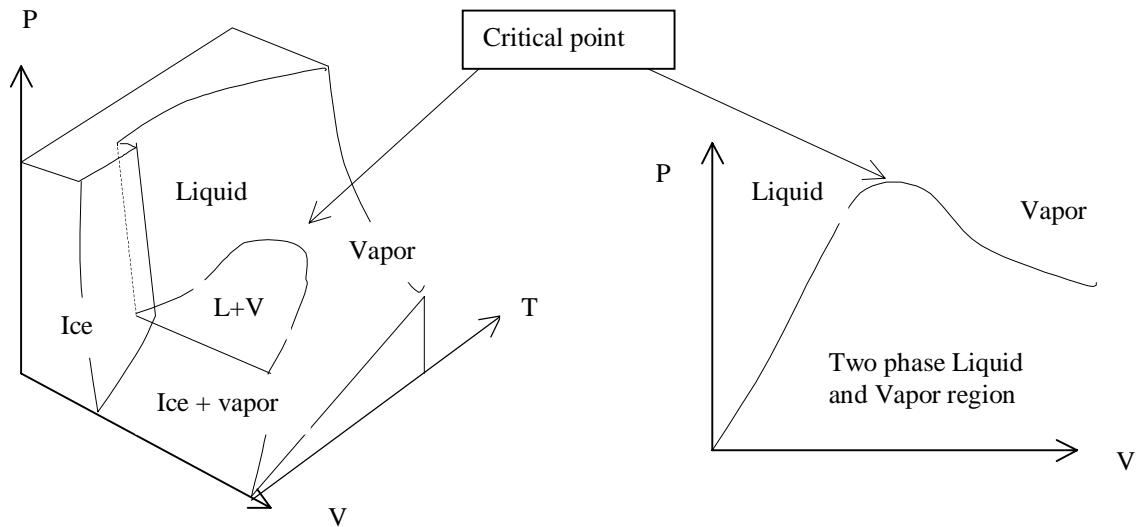


Figure 4.

a) Pressure-Volume-Temp. relation for water.

b) Simplified curve for two phases.

The Heat of Vaporization energy (HoV) for water is 2260 kJ/kg which is roughly one half of the energy release from HE per kg, e.g. TNT has about 4850 kJ/kg. Hence, the energy from 1 kg TNT has the ability to vaporize ca 1.8 kg cool, liquid water. According to table 1, the heat capacity for typical HE gases is 4 - 5 times less than for water, i.e. when mixed with a water mist, the overall temperature must decrease largely; so does also the pressure, according to the general gas law (2).

| Agent | Formula | Heat capacity C_p kJ/kg K |
|-------------------|------------------|--------------------------------|
| Carbon-dioxide | CO ₂ | 0.82 |
| Carbon-monoxide | CO | 1.05 |
| Nitrogen | N ₂ | 1.04 |
| Nitrogen-monoxide | NO | 1.00 |
| Water | H ₂ O | 4.2 |

Table 1: Heat capacities for some HE combustion products, compared to water (273K)

Different gaseous agents usually mix easily; this happens spontaneously due to the diffusion phenomenon. The mix has average values from the included agents on properties like density, heat capacity etc. As diffusion takes some time (depending on temperature, density etc.), a separation of the different gases can be maintained for some time during very fast events like shock waves, resulting in a contact surface between air and the combustion products. This can be experimentally visualized by high speed photography, and can also sometimes be traced in the pressure recordings. It is easier to observe in a simple geometry, as in a duct with smooth walls, or in free air with spherical expansion. Rough walls in a duct and obstacles inside will increase the diffusion and mixing of the gases; it will simultaneously decrease the static pressure p' of the wave front as well as its velocity.

2.3 Interaction explosive-water. Consider a water volume in the proximity of a detonating HE charge, figure 5. The expanding gas volume will, as it hits the closest water surface, initiate a shock wave inside the water volume and cause "spalling" on the opposite side of the volume.

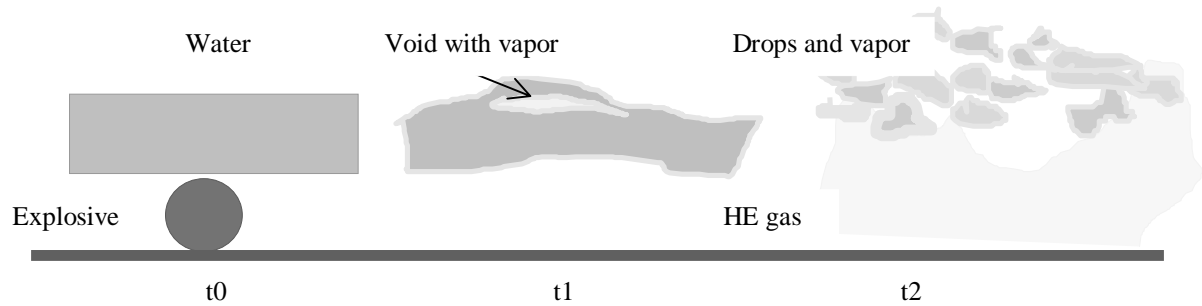


Figure 5. Possible initial behaviour of explosive-water at three stages: t_0 , t_1 and t_2 .

This will cause a void inside the water volume, which immediately fills with vapor. Due to the pressure gradient, the whole volume will also start to accelerate and be "smeared out", and because of the different velocities in different locations inside, it seems likely that the volume is somewhat later broken up into a cloud of water drops of different sizes. During this process, heat is transferred from the hot HE gases to the water, both by heat radiation and by conduction. Simultaneously, a shock wave is developed in the gas between the drops which, in the case of a confined explosion, repeatedly will affect them with heat and acceleration when the wave is reflected against the walls. This will cause them to break-up into smaller droplets which, due to the resulting large increase of the total surface area of the water, also will increase the speed of heat transfer from the surrounding HE gas.

From the above, there is reason to believe that the heat transfer to (and vaporization of) water is of large importance for an explosion in a confined space. The cooling and phase transition will, despite of a slight pressure increase from the vaporization, result in a decrease of the overall pressure; the energy of the explosive is then to a large extent stored in the water as internal energy. In free air, on the other hand, large parts of the observed water mitigation effect might instead be caused by a mechanism when the water drops absorb a great deal of the kinetic energy from the expanding HE gas and thereby suppresses the air shock wave in the surrounding space.

2.4 Analyze methods. Because of the above indicated differences in the water mitigation mechanisms due to the surrounding geometry, it is suggested to split the problem into three special cases according to figure 6. Case A: HE, water (and air) confined in a closed volume, case B: HE and water placed in free air, and finally case C: HE and water is partially confined, e.g. inside a tube with one end entering free air. Case B is only briefly treated here (more extensive in /5/, /7/ and /17/); this paper concentrates on A and C and mixes between; i.e. a chamber with an attached duct.

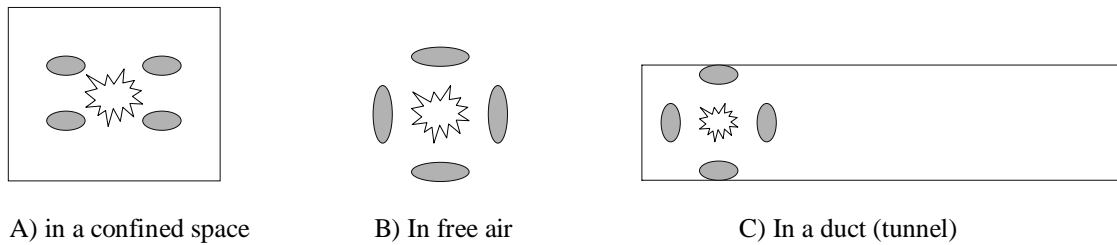


Figure 6. Suggested principal cases for the geometry around the HE –water arrangement.

A numerical model to completely simulate the situations above should consider diffusion and heat transfer, both from conduction and radiation between the HE gases, air and water. It should also deal with the formation of droplets when the water volume is crushed, accelerated and vaporized, as well as condensing of the vapor into droplets if cooled at a later stage. If the process takes place close to a structure (e.g. inside a duct or chamber) the model should deal with friction and heat transfer to the walls as well. All these extensions are today possible with advanced CFD codes, however at a high cost. As a first approach, a numerical method is suggested which is applicable for the case A and (possibly) C in figure 6. It is easily implemented by a hydrocode with a two-phase liquid-gas material model, as follows:

1. Assume that the water absorbs all of the energy released from the explosive (HE).
2. Replace HE with hot, pressurized water with similar energy, using the two-phase model.
3. Use an ideal gas model to fill the remaining space with air at NTP ("normal" pressure and temp)

When initiated, the water temperature should be close to the critical point (647 K) in order to provide a possibility for a maximum amount of water to vaporize (for a case with an excess of water compared to the HE energy, that part could be modeled as one phase material). After initiation, the water volume will start to vaporize, expand and "push" the surrounding air into shock-waves. The method is very approximate, especially for the initial interaction water - explosive; still it can illustrate some important phenomena for an explosion with high loading density in a chamber and also inside and outside an attached tunnel. Implemented on AUTODYN /9/ the model neglects heat transfer, viscosity and friction.

In the Appendix an AUTODYN model according to the above method is applied on the FOA tests described in /17/. The steel-cased 1.5 kg plastic explosive was, due ca 25% expected initial losses when the case fragmentizes, modeled as 1.1 kg PETN without water. The test with water was modeled with a similar energy in 3 kg hot pressurized water as the only "explosive". Figure 9 in the Appendix shows the test set-up, figure 10 the numerical model and the following figures (11-17) shows pressure-time histories from the target points in the numerical model and recorded data from the gages in the experiment for comparison.

3. Review of experiments (referring to the geometry cases "ABC" in figure 6)

A was investigated at FOA Grindsjon in 1994 by Forse'n (reported in /2/) where 0.5 kg HE surrounded by 2.5 kg water in plastic bags was detonated in a 1.2x1.5x 2.0 (3.6 m³) closed explosion chamber with pressure gages mounted inside. Two tests with water were compared with 0.2 kg HE without water. In both cases there was also a concrete slab mounted as one of the cubes' six walls. From earlier tests it was known, that this wall collapses when 0.5 kg HE is detonated in the volume, but after these two tests it was almost unaffected. The pressure gages confirmed this result, and it was concluded that the water reduced the "equivalent charge" by approx. 60 %. Similar tests were made by Ericsson /5/ in 1974, in smaller scale. However, all those tests must be regarded as a mix between case A and B because of their low loading density. Recently, a few small scale tests with higher density (4 kg/m³) was made by FOA /17/. Full scale tests with ammunition magazines are reported by Keenan and Wager /1/.

B was investigated by Ericsson 1974 in small scale /5/, and by Vermuelen 1995 in larger scale /7/. Ericsson tested 50 gram TNT charges surrounded by 2x, 5x and 10x its' weight by water. The charge was placed inside a balloon i.e. completely surrounded by water. The pressure was measured with gauges 0.7 meter from the charges. The results showed, that the peak pressure was reduced by approx. 5-20 % compared with bare charges, but one have to remember the scaling law for free field : $r / Q^{1/3}$; i.e. the actual "equivalent charge" was reduced by at least 50%. Recently, also tests with 20, 30 and 40 gram plastic explosive surrounded by water hemispheres up to 1 kg have been reported by Rinaudo, Smith and Rose with similar results /15/. Tests reported by Vermuelen /7/ with 10 kg HE close to approx. 1 ton water stored in specially designed water-bags ("Dellex"), resulted in a 95% reduction of the side-on peak pressure near the site and a sound reduction of 12 dB on large distances (2000 meters).

C. A few tests were made by Ericsson 1974 /5/ but has recently been closer investigated by FOA in small, medium and large scale /2/,/3/,/4/. The tests are usually not "clean case C" as they have a slight area change in the tube (large area changes are treated separately as "case A+C", below)

In small scale, a 1:20 simplified model of the "Klotz-tunnel" in Alvdalen was tested with 200 g HE surrounded by 400-600 g water in plastic cups (this corresponds to 1600 kg HE and 3200-4800 kg water in full scale). The explosion chamber was a tube with cross section 0.030 m², 1.25 m by length and was connected to a 3.75 m long steel pipe with cross-section 0.0144 m². Side-on pressure was measured in 3 locations: two gages were placed in the walls inside the pipe and one was located 1.25 m outside the pipe, right in front of the muzzle, where also a stagnation pressure gage was mounted in a few shots. Some of the results from the tests are published in /4/.

In medium scale, a number of tests have been performed with shock-tubes, most of them in "tube4" (cross-section 1.8 m², FOA Marsta), a few also in "tube3" (cross-section 4.4 m², also at FOA Marsta). The charge weight in "tube4" was 1-5 kg HE, used with and without water bags and barrels in the range 1- 25 kg. With "tube3", tests were performed with charges up to 100 kg. The measured pressure-time histories, published in /2/ and /6/, are only from side-on pressure gages, which were located inside the tunnels at quite long distances away from the explosion chamber. No measurements of stagnation or dynamic pressure were made.

In large scale, one test was performed by the "KLOTZ-Club" in Alvdalen 1996. The charge was artillery rounds, corresponding to 1000 kg HE in total. The geometry was similar to the small scale tests, but with some important exceptions: a) a tunnel crossing about 15 meters from the explosion site b) tunnel wall roughness was much larger, estimated to 0.2 m. c) the walls and the floor in the

tunnel were (probably) wet. d) a barrier was built outside, in front of the tunnel exit. Measurements were made at several locations, both inside and outside the tunnel, but no gage was mounted close to the explosion site, and no measurement of stagnation or dynamic pressure was made inside the tunnel. The results (/3/) are ambiguous; the test is briefly discussed in section 4.

A+C: Some important tests made with models of ammunition storage magazines can be regarded as a "mix" between geometry A and C. Their properties are expected to depend on some main geometry characteristics, as indicated in figure 7.

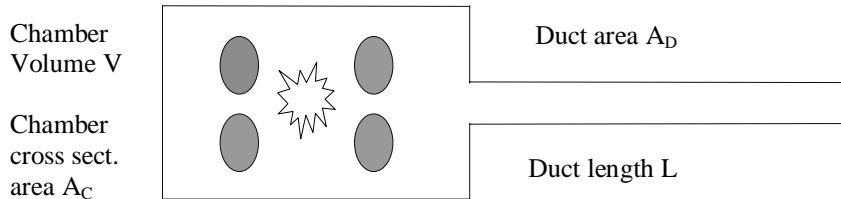


Figure 7. 'Mixed geometry' A + C (according to figure 6).

This type of structure has been tested by Joachim and Lunderman /16/. The chamber volume was 0.365 m^3 , the duct area was 0.017 m^2 and its length 4.0 m. Charge densities in the range 1.67 to 5 kg/m^3 were tested with water / explosive ratios from 0.67 up to 3.3. The water was arranged so it completely surrounded the explosive. Measurements were made of the pressure inside the chamber, and in the duct both the side-on and the stagnation pressure gages were mounted. Similar gages were also located outside the test specimen. In short, the results indicate a lowering of the pressure in the chamber by about 70 % with water present, about the same figure also occurred for the *side-on* gages, both inside the duct and outside. The *stagnation* gages in the duct, however, showed less reduction with water: about 30-40 %. The results from the stagnation and side-on gages outside the duct (located on a plane surface ca 0.4 m below the exit) had no such large differences.

FOA recently made a similar test /17/ (also treated as "case A", above). Figure 9 in the Appendix shows a drawing of the structure and the gage locations used. The chamber volume was 0.4 m^3 with an attached circular duct, area 0.053 m^2 and length 2.8 m. The charge density was 4 kg/m^3 and the water to explosive ratio 2; the water was arranged as two 'rings' around the cylindrical charge. The pressure inside the chamber was measured in 2 locations, and 2 gages for side-on pressure were located in the first part of the duct. Outside, a stagnation pressure gage was mounted on a distance of 2 meters, right in front of the duct's exit, together with a side-on gage in the same location. Altogether, 6 gages were used in this experiment. The results are quite similar to the tests made by Joachim and Lunderman, except that stagnation pressure was not measured inside the duct. Instead, the gage that was located right in front of the duct's exit (this gage had no counterpart in the Joachim and Lunderman tests) showed almost no reduction in stagnation pressure when water was present. However, considering that the stagnation pressure *inside* the duct, measured by Joachim and Lunderman, also indicated rather small reductions with water, this seems quite plausible.

The aim with the FOA tests was also to investigate if the water mitigation was affected if the charges were steel-cased or not; this refers to the Alvdalen test /3/ where artillery rounds were used. The charge in the model tests were thereby cased in a hollow, pre-fragmented steel cylinder, weighing 4.5 kg. No such effect could, however, be noted with any significance, /17/ p.12.

4. Discussion

From the experiments, it seems likely that the water mitigation works well for the principal cases A and B, provided there is, by some means, a "balance" in how the water and the explosive is arranged; the expression "balance" is used because "loading density" is only applicable to confined spaces as case A, possibly to case A-C, but not for the cases B and C.

Case A: The energy of the explosive vaporizes the water and is to a large extent stored in the HoV (this is valid for charge densities of some kg/m^3 ; low charge densities approaches case B below). The vapor is likely to cool down slowly in contact with the chamber walls, which also absorb the HoV when the vapor later is condensed to liquid water. If small leaks from holes and slots in the chamber occur, they contribute to increase the speed of the pressure decay; large leaks are treated below as case A+C. The effect of different loading densities on the mitigation capacity is briefly discussed by Keenan and Wager (/1/, Chapt.3.2).

Case B is somewhat more complicated. Only a small part of the water is likely to immediately evaporate by the heat energy from the explosive; the major part will probably remain as liquid water, accelerated by the expanding HE gases, broken up into droplets and thereby absorbing kinetic energy from the shock-wave, as described in section 2.2. Even later, evaporation and condensation may occur, close to the detonation point where the droplets and vapor relatively slowly flows out in all directions. This process will however not contribute to the fast shock-wave in free air, that is now far away from this area and hence will remain mitigated. With this explanation, it seems likely that the initial geometrical arrangement water-explosive will have a great influence on the result, which is in accordance with several experiments reported, e.g. /5/ and /15/. This is also valid for case A with low charge densities.

Case C might be the most complicated one; below some phenomena are suggested, believed to be of importance for this case. Assume that, similar to case A, the water is immediately heated by the HE, and a (partially) confined volume of air, HE gas, water drops and vapor at high pressure and temperature (however lower than without water) is formed. But, compared to case A one wall is missing, so the vapor- HE gas mix starts to expand in that direction through the tunnel, pushing the air that initially was there in front of it, which forms an air shock wave. In this situation, at least three sub-cases (C1, C2, C3) should be considered:

C1 The tunnel walls are smooth and dry; a contact surface might then occur between the mix of vapor and HE gases and the air inside the tunnel, as described in section 2.3. When the vapor behind the air shock front expands it might start to condense due to cooling from the tunnel walls, or when it expands in cool air outside the exit. When a shock-wave flow in gas phase leaves a tunnel exit, a jet is formed where the static and dynamic pressure differ significantly, as described in section 2.1. The static pressure in the wave front could be quite unaffected by the vapor, but the later arriving dynamic pressure increase is likely to be influenced, e.g. by a higher density and a change of gas velocity inside the jet. This is also in accordance with the calculated jet outside a duct attached to an explosion chamber, shown in the Appendix (figure 17).

C2 The tunnel walls are rough; the vapor and the surrounding air will now mix to a much larger extent which will put the vapor with its high internal energy closer the shock front; the front is also slowed down and mitigated by the wall roughness. It seems likely that this affects the shock front when it leaves the muzzle in some way. In order to separate such an effect from the mitigation

due to the wall roughness, a comparison with expected data from a similar one-phase flow can be made, either from empirical data or from a hydrocode calculation with viscosity, friction and heat transfer included (e.g. the RCM code “OneD” /10/).

C3 The tunnel walls are wet before the explosion, which can increase the amount of water and vapor in the flow as the shock front might absorb water from the floor and walls as it “sweeps” along the tunnel. This was indicated when the small scale tests (reported in /4/) were made. The experimentalists noted that in order to obtain reliable results, with and without water, it was important to get the test specimen completely dry between the tests. This is a memento when efforts are made to analyze the full scale test in Alvdalen, where the tunnel probably was soaked with an unknown amount of water inside, possibly also where the charge was located. This could have been the case, both for the “water mitigation” test /3/ in 1996 as well as the reference test “without water” /12/, made in 1989.

A+C ‘mixed geometry’. In the Appendix, results from the experiments made by FOA /17/ and computer runs with this geometry are shown, together with the results reported by Joachim and Lunderman /16/ they form the background for the following comments (figure 8):

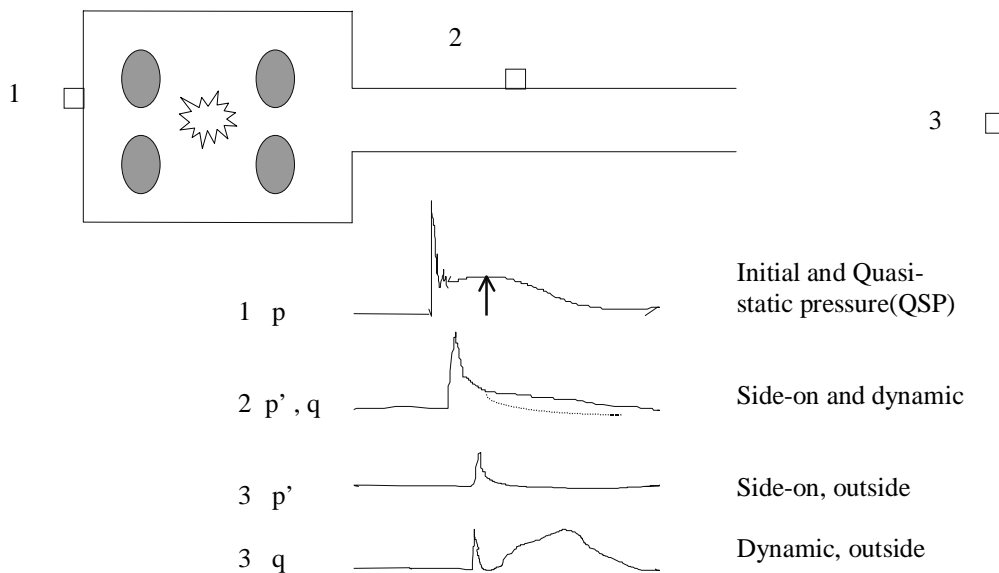


Figure 8. ‘Mixed geometry’ with typical pressure traces (not to scale)

Gage 1 first senses pressure peak from the initial wave front from the explosion, only partially affected by the water (its height is very dependent on the geometry arrangement explosive-water). Then, similar to case A above, the hot gases from the explosive builds up a Quasi-Static Pressure (QSP), as indicated in the figure. The QSP amplitude not only depends on the explosive to chamber volume ratio Q/V ; it is also affected if the attached duct’s cross-section area is large (the geometry then approaches case C). With water present the HE gases are cooled which results in less QSP build-up. (This might look like a contradiction, as the water when vaporized demands more volume and causes a QSP increase itself, but when calculated this effect is found to be much less than the former, i.e. the pressure reduction due to cooling dominates).

Gage 2 first senses the (damped) initial peak, previously recorded by *gage 1*, followed by a gas flow caused by the QSP in the chamber. The relation between the side-on and stagnation pressure depends on the density of the gas, as described in section 2.1. A comparison between tests with and without water made by Joachim and Lunderman (/16/, Table 2) shows a large reduction of the side-on pressure but the reduction of the stagnation (and thereby the dynamic) pressure is less, which indicates that the density of the flow is higher when water is present. This is expected; as was stated in section 2.2 water vapor has a much higher density than the hot gases from the explosive.

The same explanation is also relevant for *gage location 3* when hit by the steam jet outside the muzzle. The tests reported in /16/, that don't have the stagnation gages right in front of the tube exit, showed about the same low pressure as the side-on gages in the same locations. This must indicate that they were outside the range of the jet; they were located on a plane, about 3 diameters below the tube centerline. The numerical model from the FOA tests also shows that the resulting jets are rather narrow (Appendix, figure 17). The results from target point 6 inside the jet show that the flow velocity is 3 times higher without water, but as the density is then only ca 1/8th the change in dynamic pressure is almost cancelled, see table 2.

| Calculated, 20 milliseconds after expl. in target point#6 | Flow velocity | Flow density | Dynamic pressure ($q = \frac{1}{2} v^2 \rho$) |
|---|---------------|-----------------------|--|
| Without water | 1800 m/s | 0.1 kg/m ³ | 324 kPa |
| With water | 600 m/s | 0.8 kg/m ³ | 288 kPa |

Table 2. Calculated properties of the flow outside the duct (for the FOA tests).

The dynamic pressure is approx. 300 kPa in both cases, which is in accordance with the traces from *gage # 6* in the FOA experiments, shown in figure 13 in the Appendix.

4.1. Concluding remarks. From the reported analyses and experimental data, it seems that the water mitigation technique works well, concerning the quasi-static pressure for confined explosions with loading densities in the range of some kg/m³. But, if there is a small opening or an attached duct where the gases slowly leak out it can be noted that the *duration* of the QSP increases compared to a case without water. This is naturally caused by the lower gas flow velocity due to a lower pressure difference to the free air outside the structure, in combination with the larger mass present when the water vapor (and/or mist) is added to the HE gases. This increased total mass also causes a high dynamic pressure of the flow, both inside the duct and especially outside the exit; its amplitude might there be almost as large as for a case without water, despite of the reduced flow velocity. For a real situation with an exploding ammunition storage magazine with access tunnels, this dynamic pressure can cause a jet inside and outside the tunnel that is capable of throwing heavy debris quite a long distance. However, the total risk area for debris might still be reduced by the water mitigation technique, because the lower flow velocity will be unable to accelerate light debris to the very high velocities (thousands of m/s) that are typical from GP bombs detonating in free air.

Finally, it should be pointed out that there are several other mechanisms to consider for a risk analysis for ammunition storage with water than is treated here; there might as well be several possibilities to overcome the above indicated drawbacks of this technique.

5. References

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Appendix : Results from numerical model, compared to experimental data

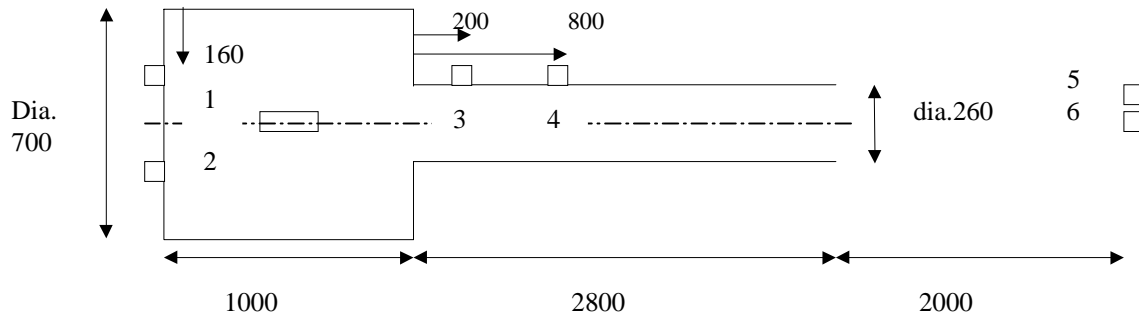


Figure 9. Test specimen (in mm). In the following pages, calculated pressure histories from target points 2 and 6 are compared with experimental traces in the corresponding gage locations.

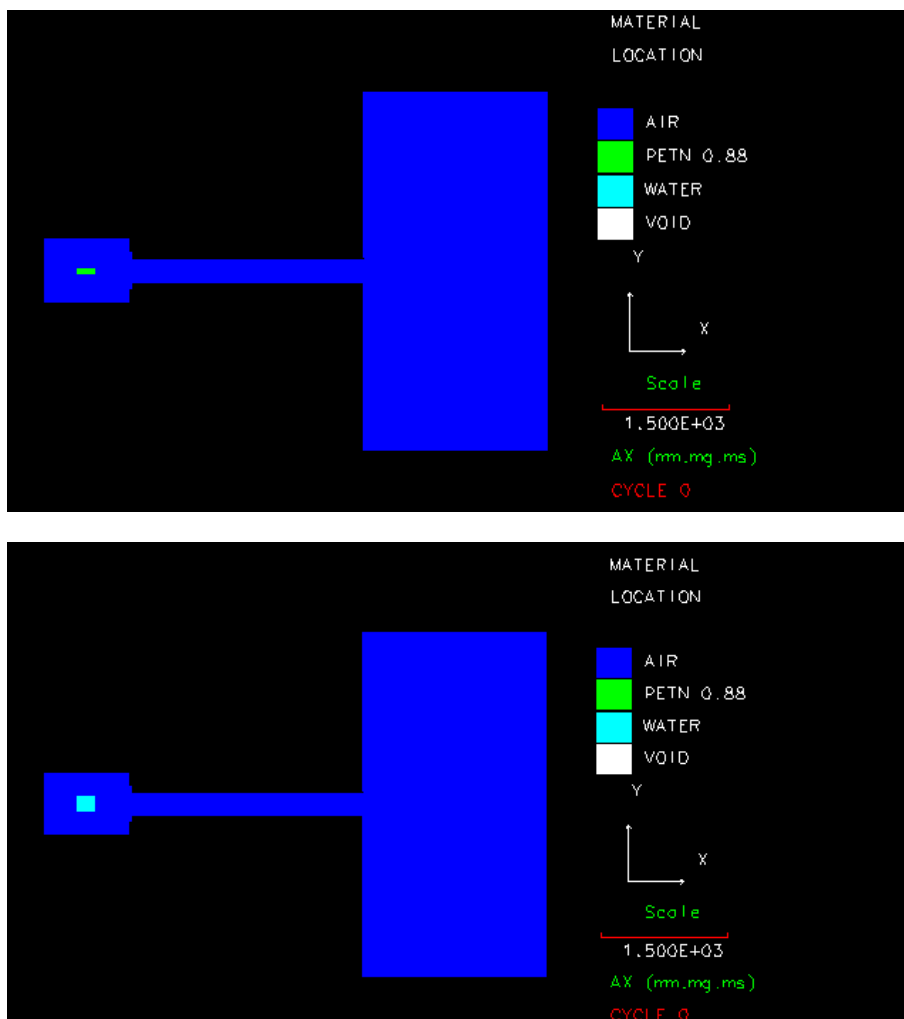
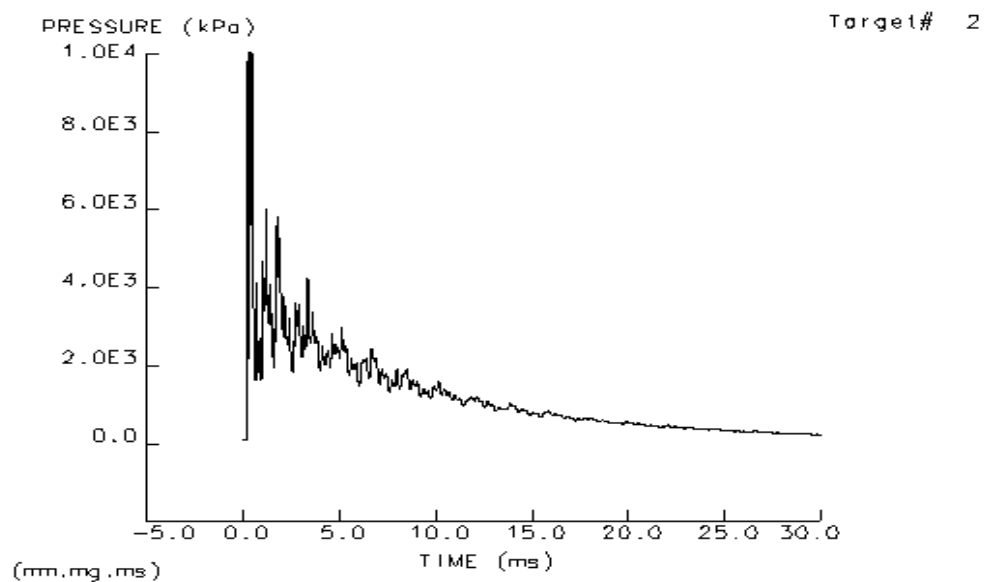
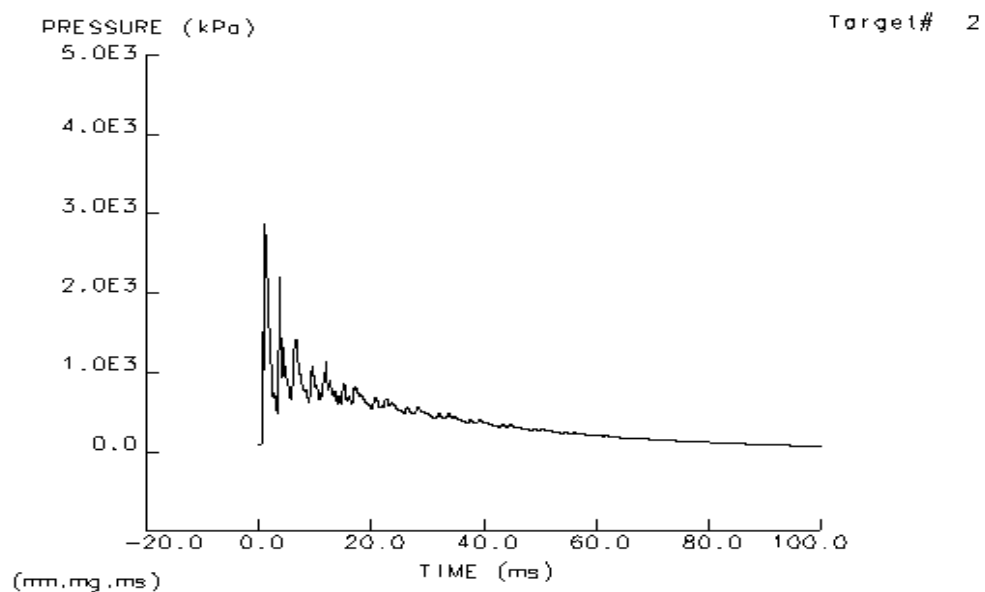


Figure 10. Numerical model on the FOA tests /17/, made with AUTODYN.



BURK21: CASED - UNCASSED CHARGES



BURK22: CASED - UNCASSED CHARGES WITH WATER

Figure 11. Calculated pressure-time history, inside explosion chamber without water (upper), with water (lower) ; note: different scales.

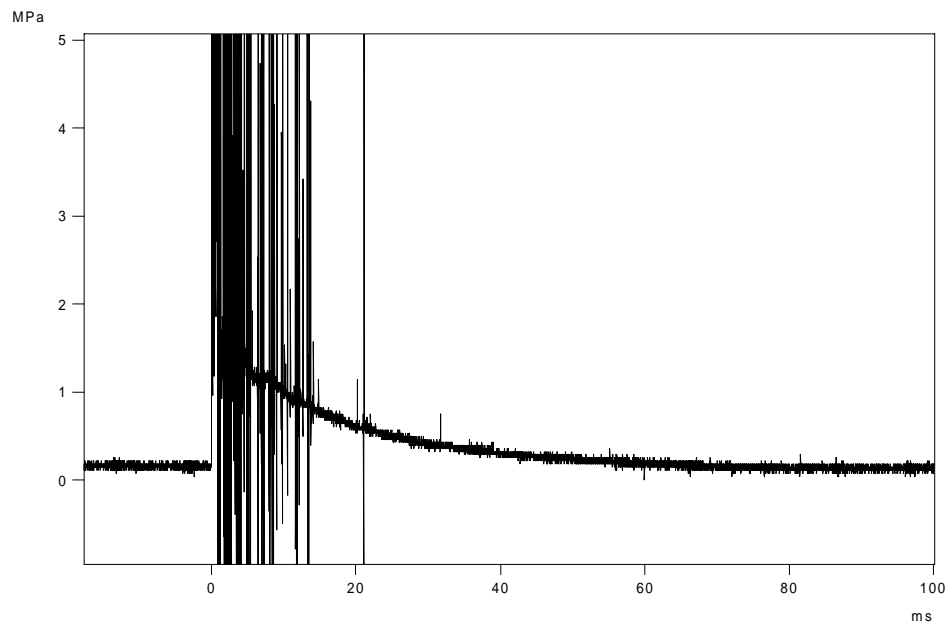
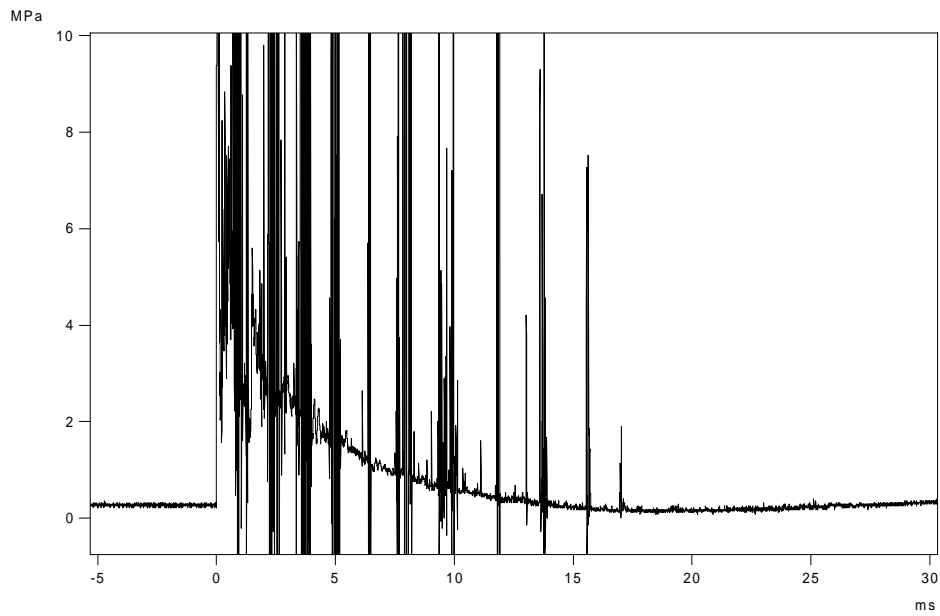


Figure 12. Experimental data: Pressure-time history inside explosion chamber gage#2, without water (upper), with water (lower)

(Note the different scales, both on pressure and time axis between the registrations. The disturbances on the traces might be caused by debris impacts on the wall, near the gage)

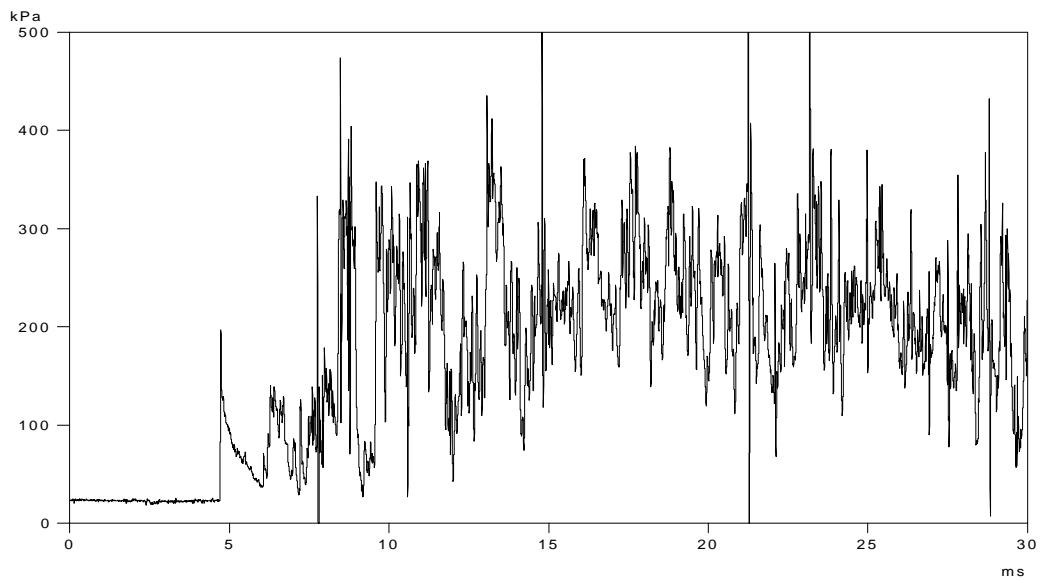
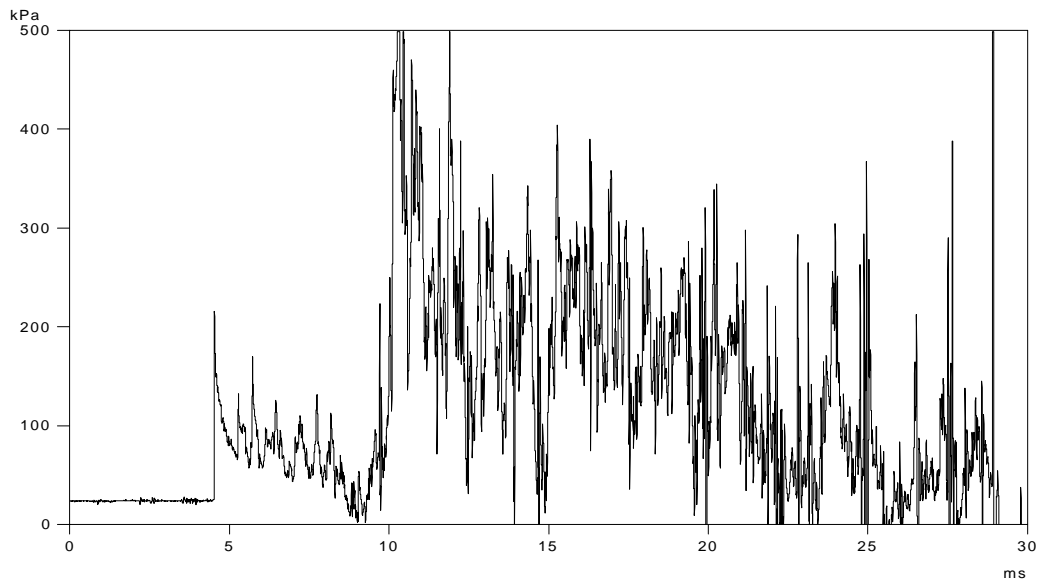


Figure 13. Experimental data: Stagnation pressure 2 m in front of duct (gage#6) without (upper), with water (lower). Approximates the dynamic pressure, except the first peak at 5 ms.

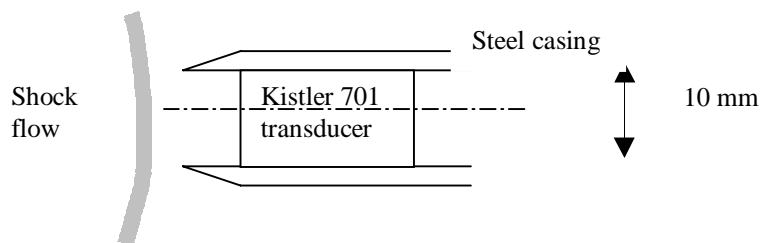
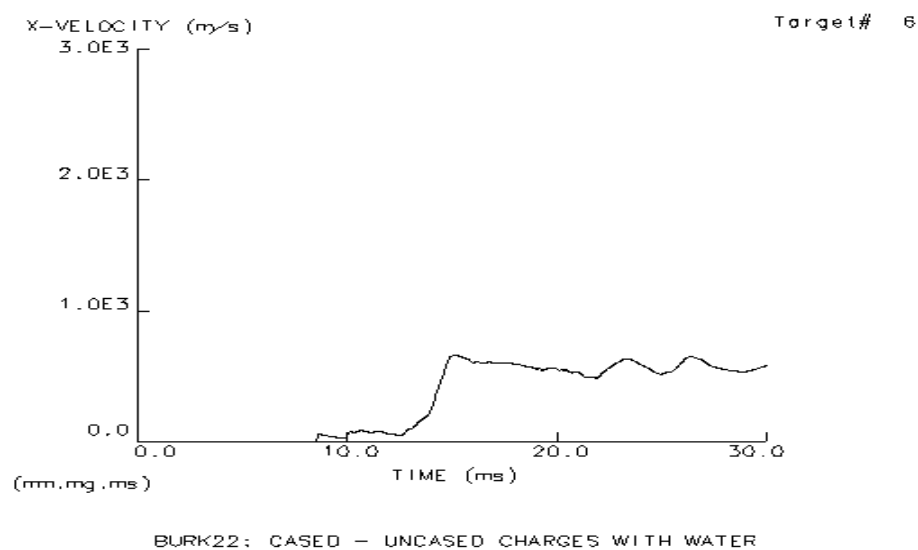
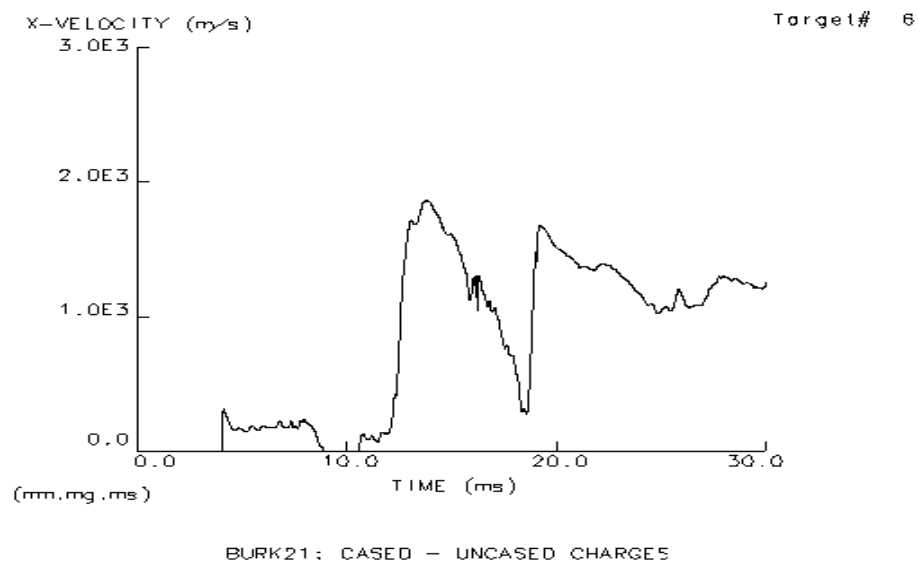


Figure 14. Principal sketch of the used stagnation pressure gage.



**Figure 15. Calculated histories of flow speed in target #6 for the two cases:
without water(upper)/ with water (lower)**

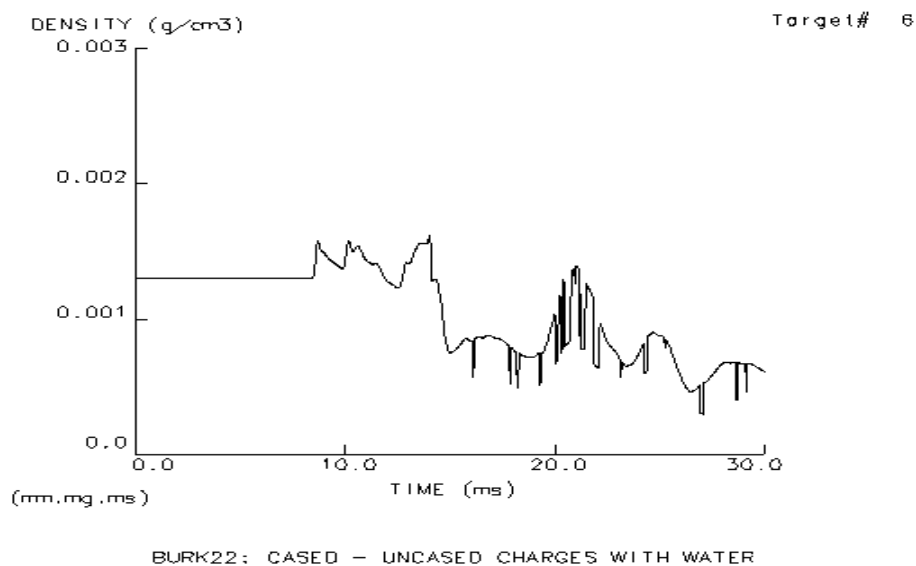
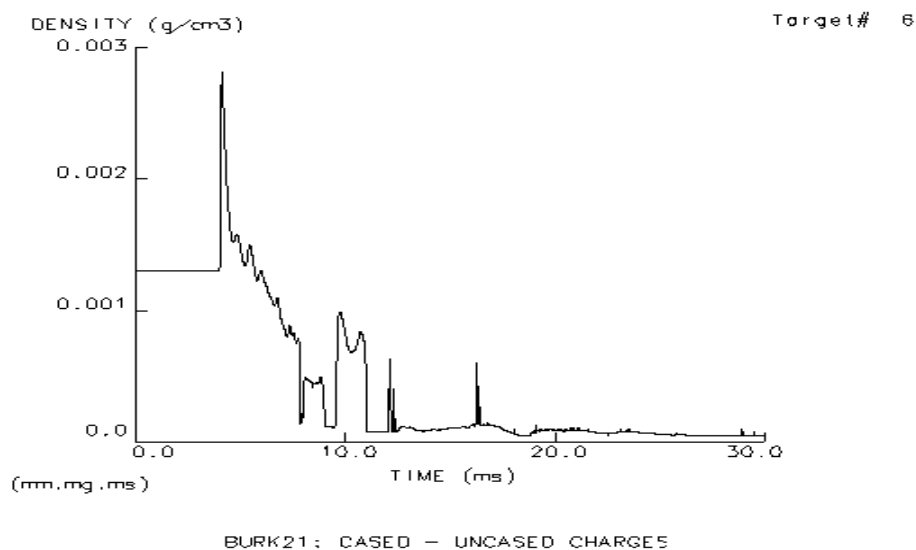


Figure 16. Calculated histories of density in target #6 for the two cases: without / with water.
 Note: The notches in the density curves are caused by the different agents (HE gas, air, water/vapor) present in the target location at different times.

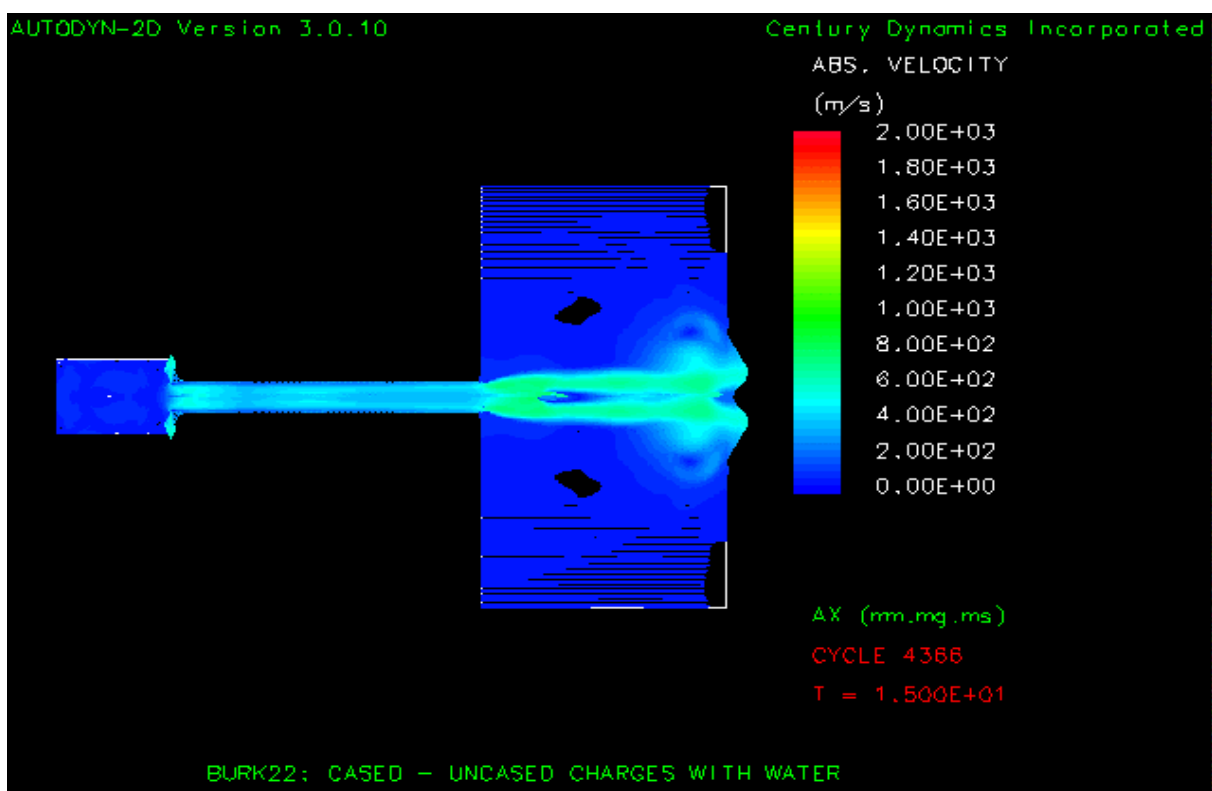
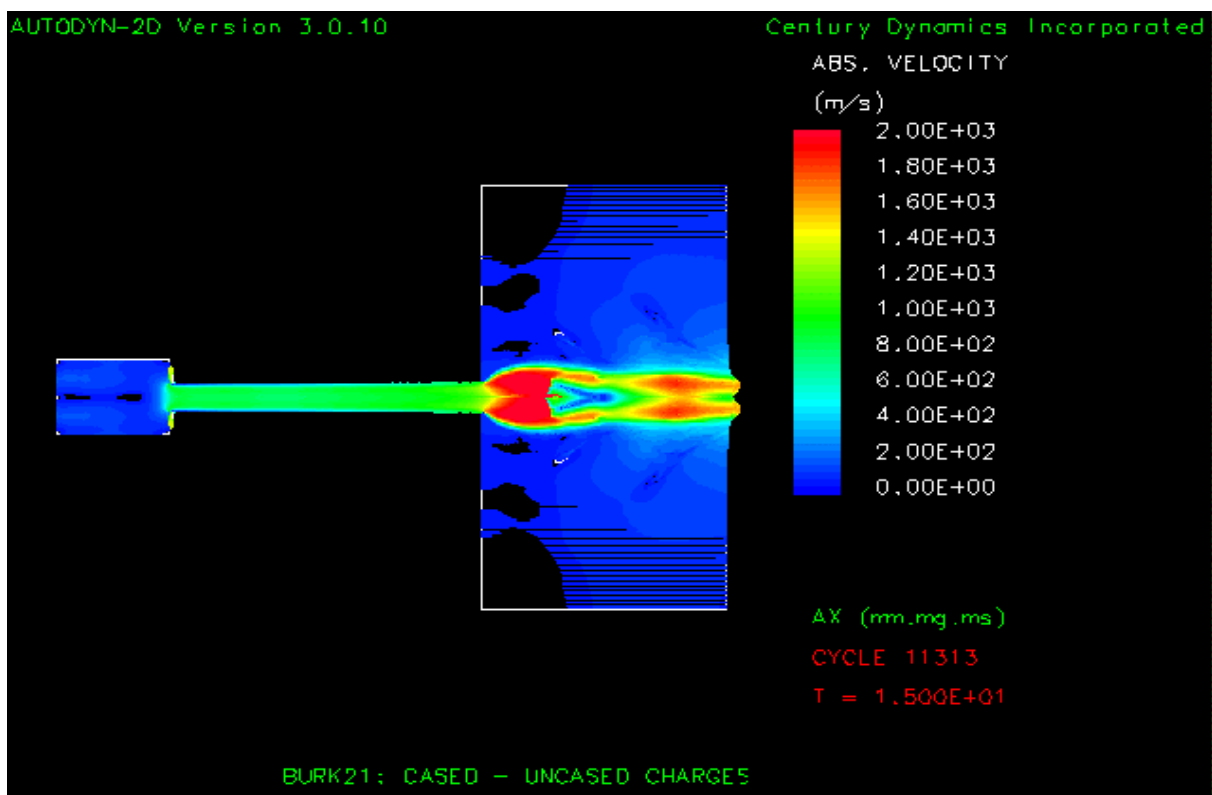


Figure 17. Calculated jets outside the muzzle after 15 milliseconds, without / with water.
Note: target #6 (inside jets) was located 90 mm from the centreline of the duct (dia. 260 mm).